

A Summary of NEETRAC On-line Frequency Response Analysis (FRA) AND a New EPRI Commercial Prototype FRA Installation at First Energy

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Abstract

The electric utility industry is in the age of transition from periodic maintenance to predictive or conditioned based maintenance on essential substation power transformers in an effort to lower maintenance costs and maximize the use of existing equipment. The development of new on-line diagnostics is in the critical path to achieve the predictive maintenance goals for power transformers.

EPRI has partnered with NEETRAC since the beginning of the on-line FRA development in 2003. The initial data from the first on-line FRA installation was recorded in 2004 and presented at the February, 2004, EPRI Conference in New Orleans, LA [10].

This paper includes key points of the current NEETRAC on-line FRA [1, 3] and the most recent developments towards a viable commercial prototype for the EPRI First Energy project. In particular, equipment upgrades and relocation as well as downsizing along with wireless data communication from the transformer are discussed for the new installation.

The commercial prototype on-line FRA is to be installed on a 345 / 140 kV, 448 MVA, auto-transformer at First Energy's Star Substation in the second quarter of 2009.

Utility Need / Background

Fault data compiled from four of the National Electric Energy Testing, Research & Applications Center (NEETRAC)'s member utilities indicates that 5.0% of distribution buses and 8.8% of transmission buses have maximum fault levels exceeding the 30 kA mark. The problem of transformer winding deformation, especially on older power banks, is increasing due to long-term exposure and the continued growth of the power grid. A practical and consistent on-line winding deformation and dielectric degradation technique would be very valuable for transformers, especially for those that benefit the most from condition-based maintenance, such as large, essential, power banks on the transmission system.

Many utilities are already using some form of off-line (transformer de-energized and switched out of service) Frequency Response Analysis (FRA) on new and existing transformers because it is well-known to be sensitive to winding distortion. At this time, FRA is the only technology that is sensitive to significant winding deformation (coils, layers, turns, leads etc.) in power transformers. A significant amount of deformation can

occur before imminent winding failure and transformer relay operations occur. After the initial winding deformation occurs, the voltage stress changes in the insulation structure which, in time, leads to partial discharge and gassing. Partial discharge and subsequent gassing usually appear for some varying time duration just ahead of winding faults. Therefore, winding deformation is one of the first and fundamental precursors to a decline in transformer condition.

There has previously been no means to perform on-line (transformer energized and in service) FRA on a transformer. Performing on-line FRA without a transformer outage, and on a continuing basis, can have a huge impact on keeping up with the condition assessment of large essential transformers. On-line FRA adds a new dimension of data to analyze the physical structure of the coils and their dielectric surroundings in a sensitive and definitive fashion while the transformer remains in service.

Unique Method

NEETRAC's on-line FRA method uses normal switching operations on the system, such as capacitor bank and reactor operations, along with lightning from local thunder storms for the FRA test signal source. The patented technology [6,7] is unique in that it can perform FRA signatures on transformer windings using a variety of input waveforms with different time and amplitude characteristics.

The software uses Spectral Density Estimates (SDE's) using the optimum transfer function / least-squares models. These are transfer function estimates that were developed and used traditionally in areas of sound, motion, and vibration studies where random signal sequences of audio frequencies and below were studied. The application of SDE's to High Voltage Impulse Testing and Harmonic Characterization of Power Apparatus using a series of tailored pulses was initially developed by NEETRAC over eighteen years ago [5,9]. The application of spectral density estimates for off-line and on-line detection of power transformer winding deformation has been developed and made possible by the recent emergence of high quality low cost digitizers, faster and more powerful computers, and new digital computational methods.

When defining spectral densities for a single input / single output system, there are three spectral densities which are computed after the input and output pulses have been acquired. The first are auto-spectral densities and the last is a cross-spectral density. These three functions are computed in the frequency domain as follows:

$$G_{xx} = X(f) * X(f)$$

$$G_{yy} = Y(f) * Y(f)$$

$$G_{xy} = X(f) * Y(f)$$

Where

G_{xx} is the auto-spectral density of $x(t)$
[can be described as the FFT of the time domain auto-correlation of $x(t)$]

G_{yy} is the auto-spectral density of $y(t)$
[can be described as the FFT of the time domain auto-correlation of $y(t)$]

G_{xy} is the cross-spectral density of $x(t)$ with $y(t)$
[can be described as the FFT of the time domain cross-correlation of $x(t)$
& $y(t)$]

An asterisk (*) denotes complex conjugate

Using the above-calculated functions, the $H(f)$ and Coherence can be estimated, and the Random Error of the technique can be minimized. Note: Bias error is minimized by using calibrated instruments and good high voltage test technique. The coherence function describes the amount of magnitude and phase linearity of the system as a function of frequency. It is also used to determine which points in the estimate for $H(f)$ are considered as valid and also provides a figure of merit for the error magnitude of $H(f)$ when plugged into the appropriate error equation for $H(f)$.

Spectral Density Estimates reduce random noise in the measurement by taking advantage of several features. The cross-spectral density calculation uses only those components of the output pulse that are correlated with the input pulse. For this reason, any un-correlated noise in the output is rejected. The information from each individual input and output pulse is retained while the noise in the low amplitude output pulse is rejected. The Auto-spectral density calculations remove the un-correlated (non-periodic) noise from the signal of interest. In addition to noise reduction, these features allow the composite 3 phase neutral data to be effectively separated into the individual phase components on a 3 phase auto-transformer with all three phases in one tank with one neutral connection.

The frequency response function which best fits the application of the on-line (and off-line) FRA technique is

$$H(f) = G_{xy}(f) / G_{xx}(f)$$

This equation for the $H(f)$ estimate reduces noise further if the signal-to-noise ratio is highest for the input $x(t)$.

Since the data is non-repetitive or statistical by nature, it is necessary to perform about 3 to 5 averages in the frequency domain of the SDE's given above and the outcome of $H(f)$ is enhanced further if the corresponding input, and therefore output, pulses are different or slightly different in the time domain. This attribute enhances the on-line technique of using pulses which occur normally on the power system.

The Coherence function is given by the following:

$$\gamma^2_{xy}(f) = |G_{xy}(f)|^2 / G_{xx}(f) G_{yy}(f)$$

The Coherence is a real valued function having a magnitude ranging from zero to one. A value of one would indicate a perfect linear relationship of magnitude and phase from input pulse to output pulse and a value of zero would indicate a complete non-linear relationship. The coherence function is very sensitive to relatively small errors in the

magnitude (or phase) estimate for $H(f)$. So data should not be considered invalid when the coherence function is not equal to one, but should be weighted accordingly. It is observed from experience that very good data usually produces Coherence values in the range of 0.8 to 1.0 for this type of test technique while Coherence values down to 0.4 still provide some useful data with appropriate considerations. The Coherence function is also sensitive to noise in the input pulse and output pulse due to digitization error and any extraneous noise in the input pulse. Note that, by definition, the chosen SDE computation of $H(f)$ minimizes noise in the output pulse which is not directly correlated with the input pulse.

Please refer to the references for additional details on the use of spectral density estimates.

Bandwidth Considerations

Traditionally FRA field test frequencies in the megahertz region have just been a curiosity or have been largely ignored because of noise, errors, equipment cost, and not enough information with the existing equipment etc. However, according to the theory of modern turn-to-turn transformer winding models, the higher frequencies are more sensitive to winding deformation [8]. So if the FRA test equipment is designed to effectively mitigate the problems associated with the higher test frequencies, the resulting FRA test is more sensitive to winding deformation. In fact, the increase in sensitivity is such that a simple rule set can be utilized in software to make decisions on winding deformation without the need for expert test personnel to observe the relatively small variances in the transfer function at the lower frequencies [9]. Therefore, the application of SDE's in an on-line algorithm offers bandwidth and test sensitivity advantages.

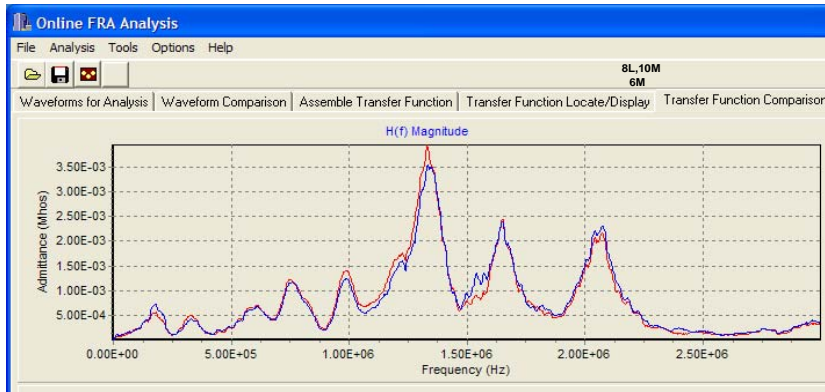
Florida Power & Light Company (FPL) On-line FRA Installation

The FPL location is our second on-line FRA installation, but it is our first attempt to perform on-line FRA on a three phase auto-transformer with all three phases in one tank with one external neutral bushing. FPL began recording on-line data on April 19, 2005 for the Plumosus 230 / 138 kV, 400 MVA, three phase, auto-transformer with TCUL (tap change under load). The O'Hara development work, our first on-line FRA installation, is on a 500 / 230 kV auto at Georgia Power, which is made up of three single phase units with access to all three external neutrals. Due to inherent single phase isolation the phase source and neutral current contribution for the corresponding phase are automatically known for O'Hara. In contrast, FPL's technique must be able to separate the three phase influences from one composite neutral waveform, determine which phase is the source of the input pulse, and determine whether the input source is the H or X winding.

Winding Comparisons: Before vs. After 2005 Hurricane Season in South Florida

It is important to demonstrate that when an FRA measurement is repeated at a later date and the winding conditions have NOT changed, that the same FRA signature can be repeated on the follow-up test. The graph in **Figure 1** represents the two transfer function (TF) magnitudes from the X2-H0X0 winding of the Plumosus transformer.

X2H0X0, Same-Winding Comparison: Before vs. After 2005 Hurricane Season in South Florida



Conclusion: NO SIGNIFICANT CHANGE for X2H0X0 & Demonstrates REPEATABILITY

Figure 1

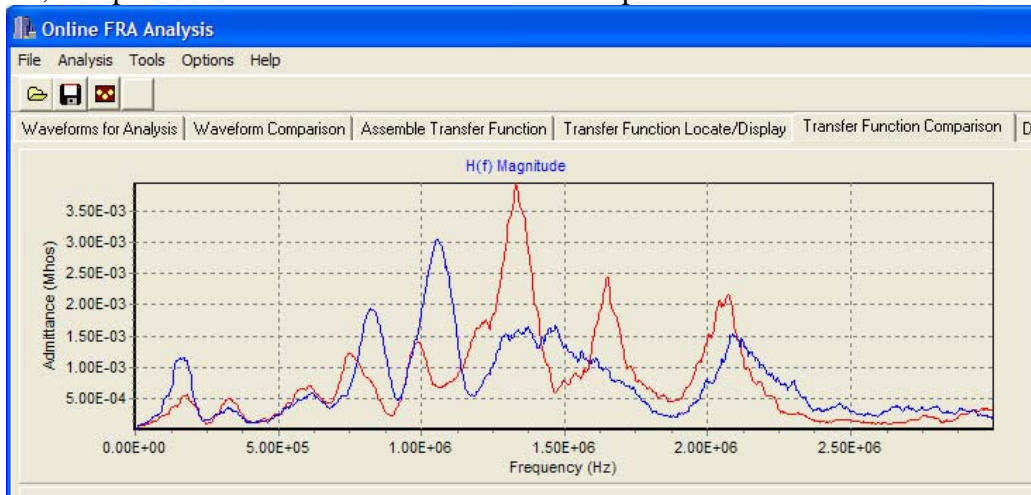
The two TF's are very similar and do NOT need to be direct overlays to indicate NO change in the X2-H0X0 winding from past (before 2005 hurricanes) to present (after 2005 hurricanes). The blue trace is the TF for the first time period and the red trace is the TF for the second time period. The similarity of the TF before and after magnitude traces indicate that there was NO significant X2-H0X0 winding or insulation damage during the 2005 hurricane season. In addition to indicating no significant hurricane damage, the results also indicate good repetitive data over the span of about one year, from before to after the June-to-October hurricane season.

On-Line FRA Test Sensitivity

The FPL auto-transformer has a “plus 8” to “neutral” to “minus 8” tap position TCUL which ranged from 2L to 2R during the last year of FRA monitoring. The tap position is checked and recorded in the database immediately before digitizer waveform download because a change in tap winding connections results in an FRA signature change.

FPL began FRA monitoring on this transformer assuming that the TCUL would remain on the same tap throughout the test. However, Florida experienced its first hurricane in 2005 and FPL operated the tap changer remotely about 200 times during one month. After the hurricane season, NEETRAC installed a TCUL position monitor to record the tap in the database along with the other data information. We were unable to record tap positions for about 5000 pulse records during that storm season, but still had about 1500 records with known tap positions before the hurricanes began, and about 1500 records with recorded tap positions after the hurricane season ended. As few as 3 to 5 pulse records per winding are required for valid FRA calculations after the hardware pulse selection and the software filtering of the database.

Although experiencing much unusable data with unknown tap information, the installation of the TCUL position monitor proved to be a very valuable step in determining the detection sensitivity of the on-line FRA technique. For example, after the TCUL monitor installation, FPL was able to easily detect the change of one tap position, from 1L to 2L from the on-line FRA traces. Of the 3000 pulse group with tap positions recorded, about 2000 of these were on tap 1L, and about 900 were on tap 2L, and 100 were on 2R. The FRA graphical results are shown in **Figure 2**. The most significant differences for tap 1L versus 2L data are the frequency shifts in the resonance peaks in the magnitude plot along with the absence of a peak at about 1.65 MHz on tap 2L, compared to the transfer function data for tap 1L.



On-line Results, X2-H0X0, Tap 1L (red) Compared to Tap 2L (blue)
Figure 2

This demonstrates the good sensitivity of the on-line FRA method to a relatively small change in the overall X winding.

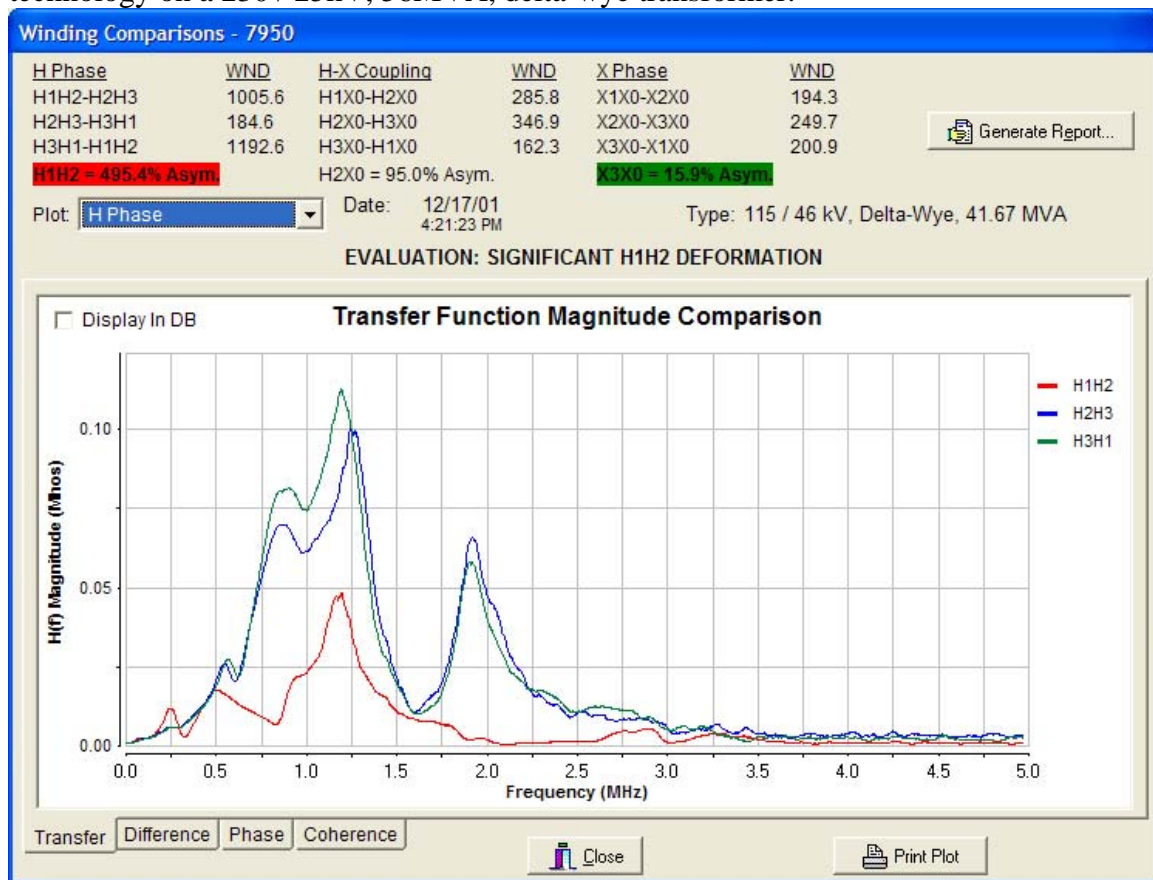
A Reference Example for Winding Insulation Damage

In order to get an idea of how much change in an FRA trace is significant, we must document the variance in FRA characteristics for known winding deformation and insulation damage.

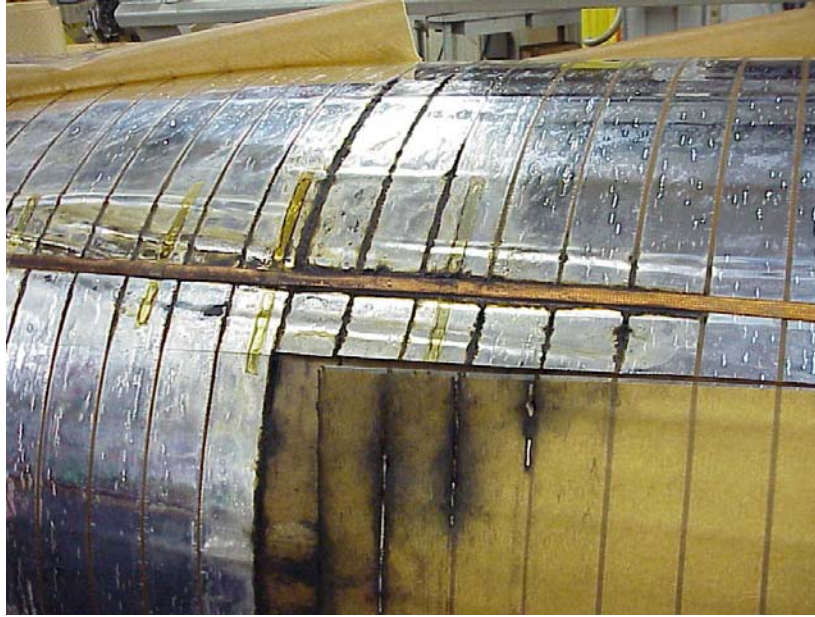
Here is an example of an FRA test result using the NEETRAC FRA technology in which significant winding insulation damage was detected. **Figure 3** is an off-line example from the GA Power system on how different the TFs are, using the NEETRAC technology, when a winding insulation has damage. This is the test result using the Phenix FRA-100 off-line test set (NEETRAC technology) to test a transformer taken out of service by GA Power due to 120 ppm of acetylene on a routine DGA. The power factor and TTR indicated normal, but the off-line FRA test indicated an abnormal phase in the high side delta. As can be seen from the graph, the H1H2 winding is significantly different in frequency peak location, and a missing frequency peak at 2 MHz, as compared to the other two phases. This is a cross phase comparison test because we had no previous history on this transformer for a historical same-winding comparison. The cross phase

test works well here since a transformer of this type, in normal condition, does not have extreme differences between phases, as evidenced by the similarity of the other two phases.

After the FRA field test, the transformer was un-tanked at the GPC Repair Shop and visually inspected for “acetylene damage”, but nothing was found. The coil assembly indicated by FRA to be significantly different was taken to the local manufacturer and unwound. The results are shown in **Figure 4**. The bond between the copper ribbon and the inner static shield on the H1H2 winding had lost good contact and began to produce small arcs and carbon deposits. This transformer was switched out of service. It did not differential or over-current trip. The amount of acetylene had been trending upward over a period of months while in service. Note: The NEETRAC FRA technology will indicate a winding problem whether it is a dielectric problem as shown or a winding physical problem such as turn, layer, lead displacement or significant winding looseness. **Figures 5 & 6** demonstrate the effects of winding buckling using the NEETRAC FRA technology on a 230 / 25kV, 56MVA, delta-wye transformer.



Phenix FRA-100 test result indicating winding damage on off-line transformer
Figure 3



**Insulation Damage Found by Unwinding Coil Assy.
Figure 4**

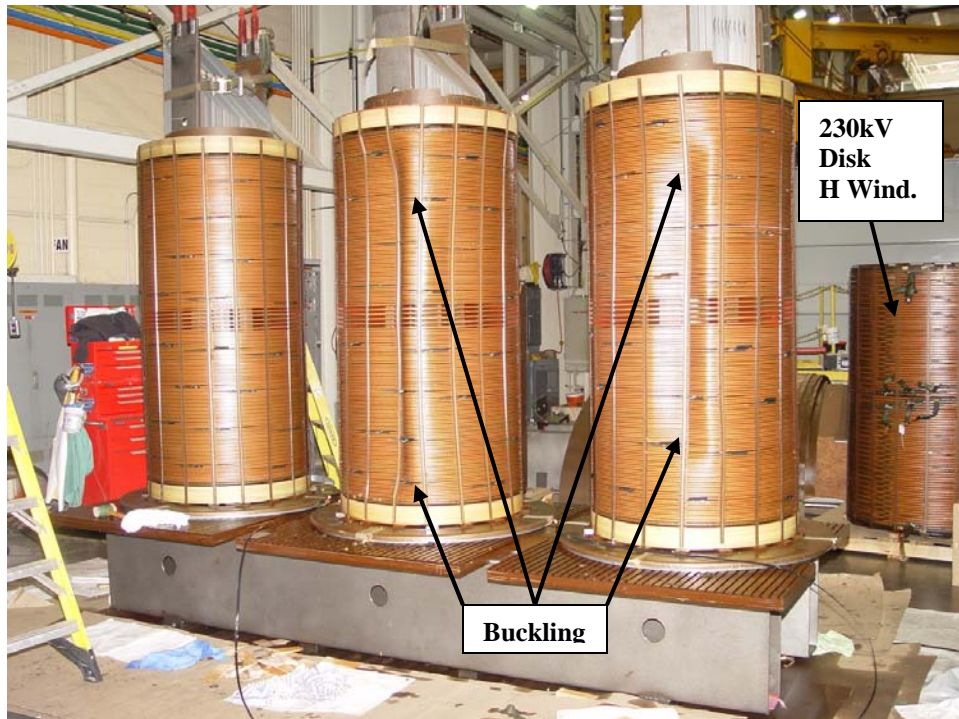
Off-line Case Study from SoCo System Multiple X Winding Buckling

NAMEPLATE: 230 / 25 kV, 56 MVA, delta-wye, Westinghouse,
mfg1985

Status: Internal Fault / Bank Differential Relay Target

Tests Passed: Power Factor, Megger, TTR

Tests Failed: Un-tanked inspection at repair shop, FRA-100 OWA
test



Buckling found on 2 of the 3 25kV helical windings.
Figure 5

Multiple X Winding Buckling

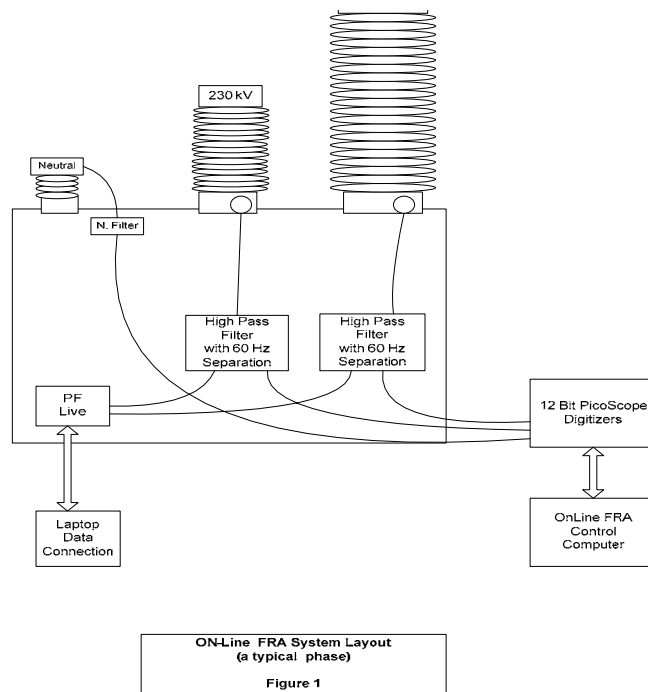


All 3 magnitude and phase traces are significantly different when 2 of the 3 windings are damaged (buckled).

Figure 6

SoCo On-line FRA Installation

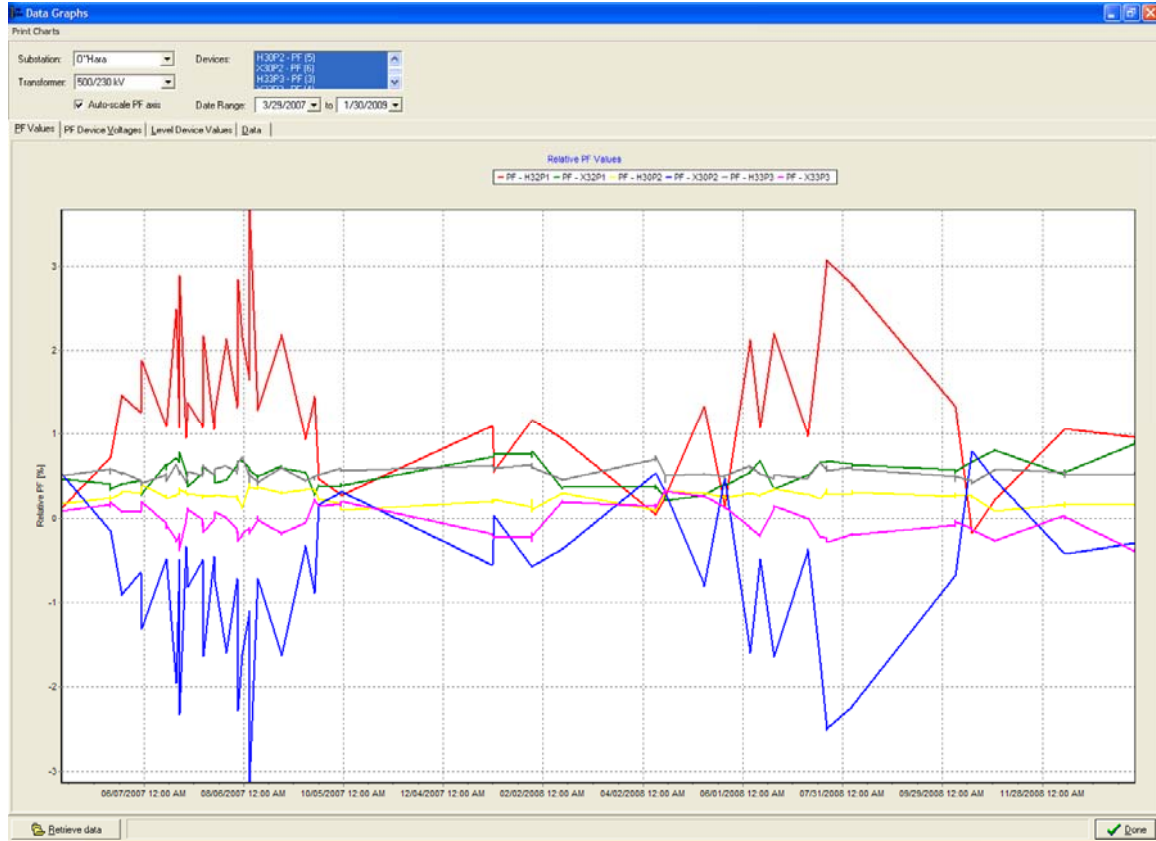
NEETRAC currently has two on-line FRA development installations. SoCo's Georgia Power O'Hara transformer is the location of the initial installation and the continuing development work. The first on-line FRA equipment was installed in October, 2003, and several upgrades have occurred since then. The on-line FRA system block diagram is shown in Figure below.



The O'Hara auto-transformer is made up of three 500/230/kV, 672 MVA, single phase units. The 500 kV and 230 kV capacitive bushing taps are coupled with purpose-designed high pass filters to enable transient data for FRA and 60 Hz data for bushing relative power factor to be gathered simultaneously. The FRA signature of a winding is affected to some degree by bushing condition, so the bushing PF is monitored to indicate bushing problems [12]. In addition, there are certain bushing indicators from portions of the winding FRA data.

One of the effects of long-term bushing aging and / or the beginning of bushing failure is the increase in power factor with bushing temperature increase. This effect is shown in **Figure 7** by a screen shot from the On-Line Monitoring Inc.(OMI), PF Live[®] relative power factor equipment, which works simultaneously with the on-line FRA from the same bushing taps. The red and blue traces represent bushings that change power factor

with a change in bushing operating temperature over time. **Figure 7** shows the trend of increasing on-line relative power factor for a 500kV bushing to over 3% during the summer months from 2007 to 2009, and therefore this transformer bushing should be in the path for replacement.



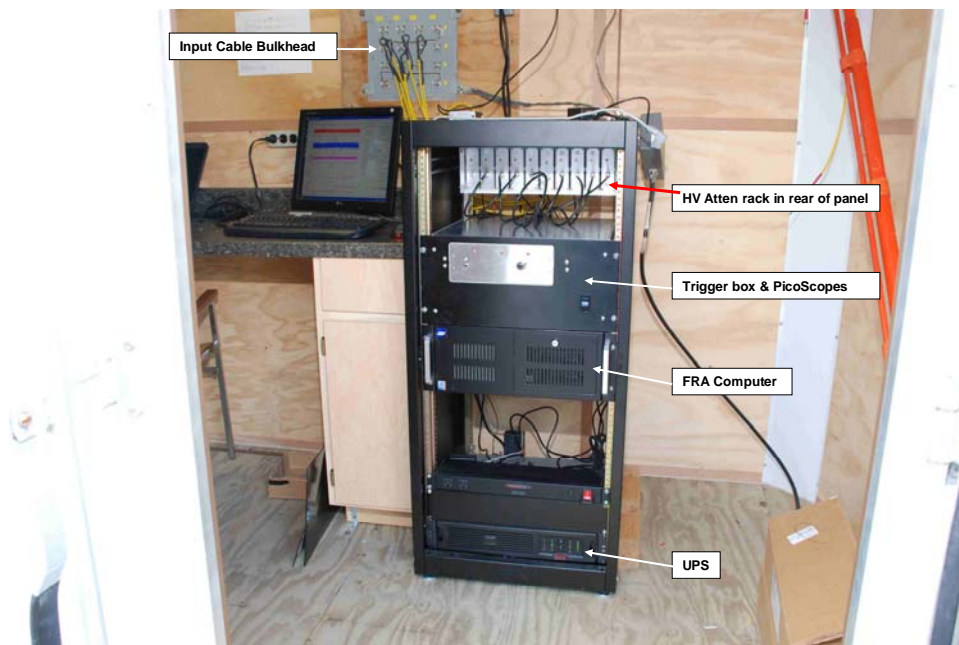
Relative PF [%] vs Time of Test
Figure 7

In addition to using the H and X bushing taps for on-line FRA, a high pass filter is installed directly across the neutral bushing with a physical mounting on the side of the transformer. This is mounted just after a 27 kV cutout for maintenance access and neutral BIL integrity. See reference [2, 10] for installation details.

Figure 8 shows the FRA trailer set-up at O'Hara Substation, and **Figure 9** shows the digitizers and computer inside the trailer.



O'Hara FRA Equipment Installation
Figure 8



FRA Equipment Inside Trailer
Figure 9

Voltage Divider Installation

An outdoor laboratory grade wideband voltage divider was chosen for installation near the 3 phase, 2000 MVA, 500 / 230 kV auto-transformer, phase 1, to record and analyze actual transients on the 230 kV bus. This divider will ultimately validate the software corrections to the transients recorded from the transformer bushing taps so that accurate EHV transient records can be made from the bushing taps without the presence of a voltage divider. The bushing tap data must be corrected to represent the bus data since the bushing has its own transfer function with its characteristic resonances that influence the measurement. Note that the voltage divider is for reference and software validation in our development project and is not required for new on-line FRA installations.

The divider was provided by Bonneville Power Administration (BPA) and has a specification of dc to 1 megahertz with a 1% ratio accuracy up to 400 kV dc and 320 kV rms ac. The divider is installed near the X1 bushing which has a nominal 132 kV of phase-to-ground voltage. See **Figure 10** and Reference [11] for the divider installation.



BPA Divider Installation @ GA Power
Figure 10

Divider Withstand & Calibration Tests

The transportable divider was first erected in the NEETRAC High Voltage Laboratory for ac and impulse withstand testing along with ratio calibration according to IEEE Std. 4 – 1995 [4].

Key Features of O'Hara Development

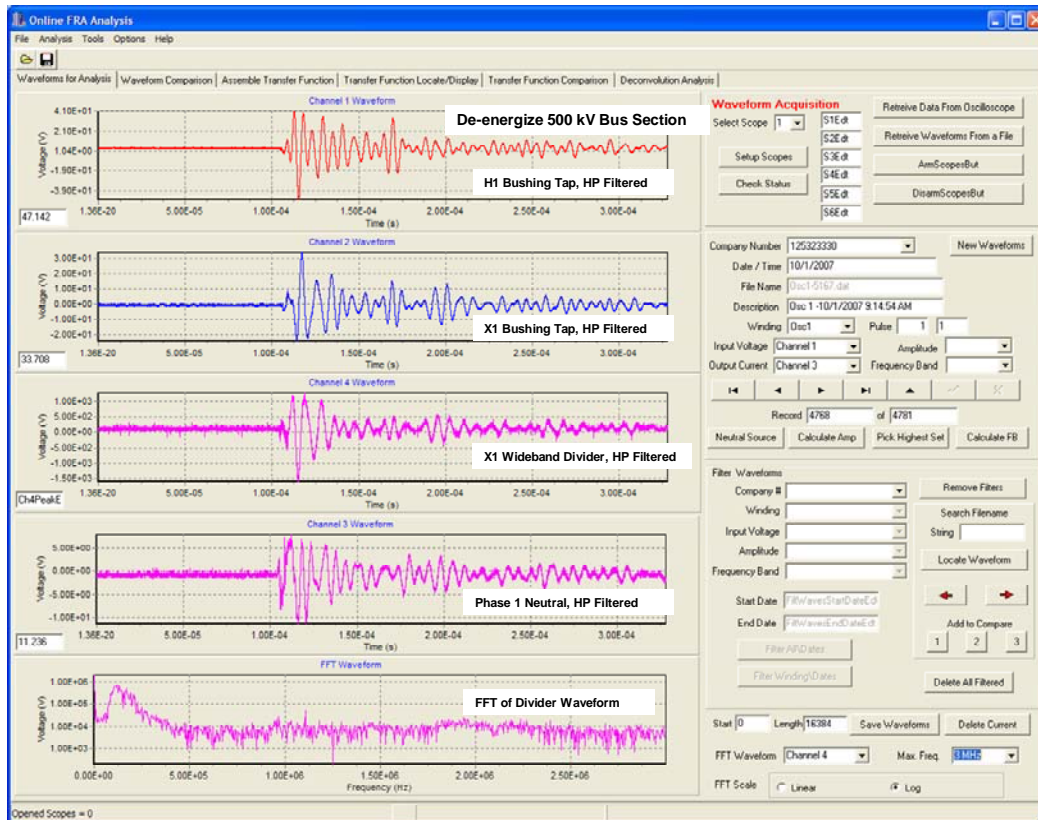
- Proved concept of on-line FRA and that it can be performed in a practical and economical manner, with a bandwidth of at least 2 MHz
- Demonstrated that on-line FRA can be performed at the 500 kV level and the equipment can survive system switching and local lightning storms
- Demonstrated that on-line relative PF of the transformer bushings can be performed simultaneously with on-line FRA
- Showed a season to season match with on-line FRA traces using separate data
- Obtained a frequency peak match for off-line FRA versus on-line FRA trace magnitudes using the 12 bit digitizer upgrade

De-energizing 500 kV Bus Section @ SoCo Substation

The high side of the 500 / 230 kV auto-transformer is a ring bus consisting of four 500 kV transmission lines. The 3 phase bus section for this ring bus, that was de-energized by a motorized disconnect switch, is 950 feet in length. The disconnect switch is located about 300 feet from the high side of the on-line FRA test auto-transformer.

The wideband voltage divider output is recorded simultaneously with the outputs of the H, X, & Neutral bushing high pass filters for the phase 1 auto-transformer [11]. The high pass filters are maximally flat, linear phase, 3rd order filters to minimize the large 60 hertz components in order to maximize the dynamic recording range of the high frequency transients [2,10].

The waveform captures for de-energizing the 950 feet of adjacent 500 kV bus section are shown on the on-line FRA software window in **Figure 11**. These waveforms are triggered by the first transient from the opening switch to go above the trigger level of the recording equipment, so the waveforms presented may not reflect the highest level transients generated for this event. The intent was not to capture the highest transient magnitude levels but to show the frequency content of the transients on an EHV bus and their ability to travel through the transformer windings of a large power transformer.



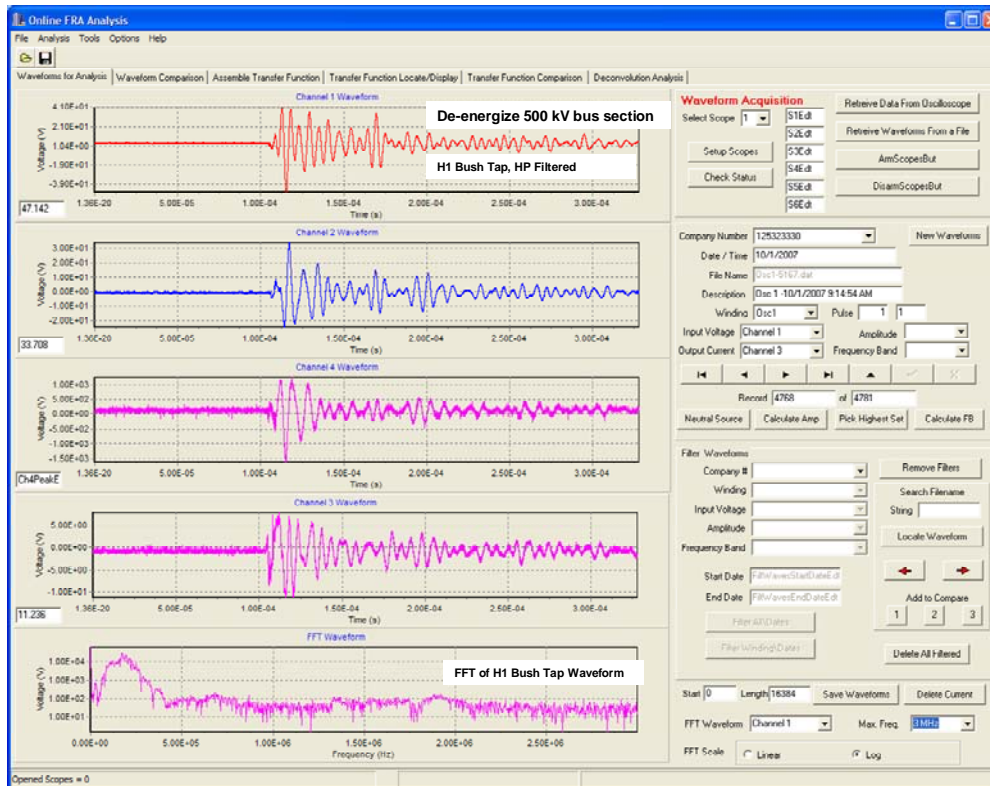
H1, X1, Neutral, & Divider Waveforms, & FFT of Divider Waveform
Figure 11

Observations:

The most dominant frequency for this on-line event is about 175 kHz at the H1 bushing tap (channel 1). A slightly lower frequency with a 2.7 kV peak-to-peak is recorded by the wideband divider next to the X1 transformer bushing (channel 4). The X1 bushing tap record (channel 2) is also similar to the wideband divider trace. The same dominant frequency can also be observed at the transformer neutral (channel 3). So the “ringing” observed from the H1 and X1 bushing taps and the neutral bushing are not a result of the bushing characteristics but are the actual 500 kV-through H1 winding-through X1 winding- to phase 1 neutral response to the opening 500 kV switch. We also know from performing an off-line FRA of the bushings with their associated filters and cabling that the H and X bushing responses are flat near 175 kHz, so it is reasonable to expect the X1 bushing tap trace to be similar to the wideband divider waveform at this frequency.

We also observe from the FFT of the divider waveform at the bottom of **Figure 11** that the FFT voltage is considerably above the baseline for frequencies below 500 kHz and slightly above the baseline for frequencies in the 1MHz to 2MHz region. This is also an indicator that some of the high frequencies are passing through the transformer windings.

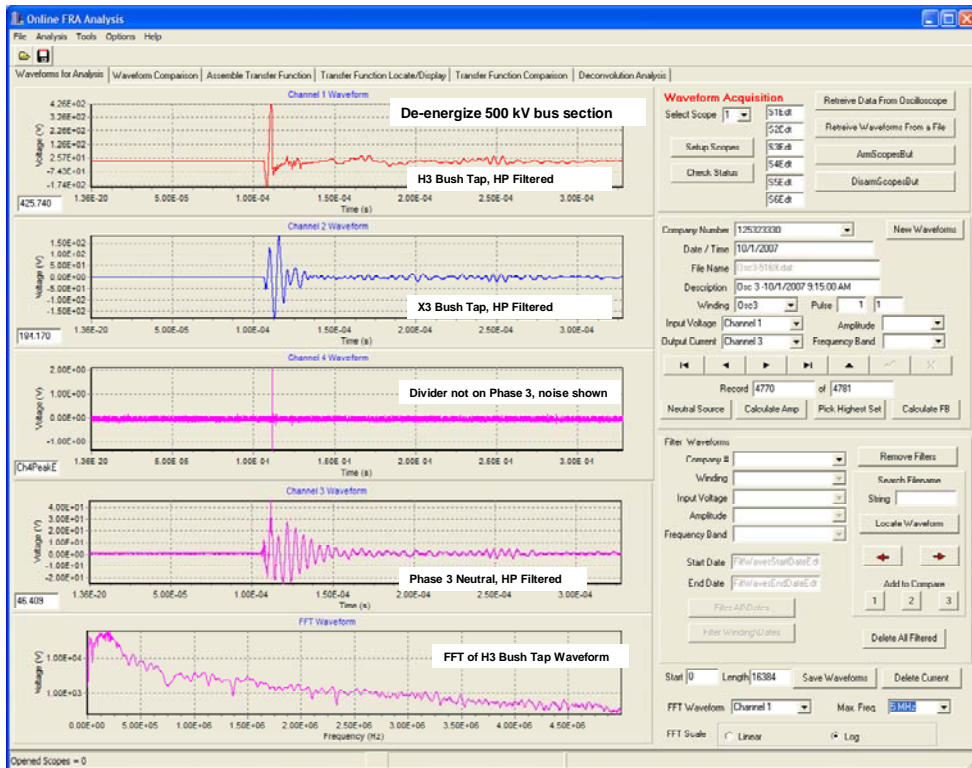
Figure 12 is the same as **Figure 11** with the exception that the bottom trace is an FFT of the H1 bushing tap waveform which also shows frequencies higher than the baseline up to about 2 MHz.



H1, X1, Neutral, & Divider Waveforms, and FFT of H1 Bushing Tap
Figure 12

Figure 13 shows the waveform captures for phase 3. In this case, the transient recorded from the 500 kV switch opening is much larger in magnitude with higher broad band frequency content. The numbers inserted to the left of each of the waveform graphs indicate the peak voltage recorded for the respective waveform record. The H3 trace of **Figure 13** indicates a peak of 426 volts compared to the 47 volts peak of the H1 trace shown in **Figures 11 & 12**.

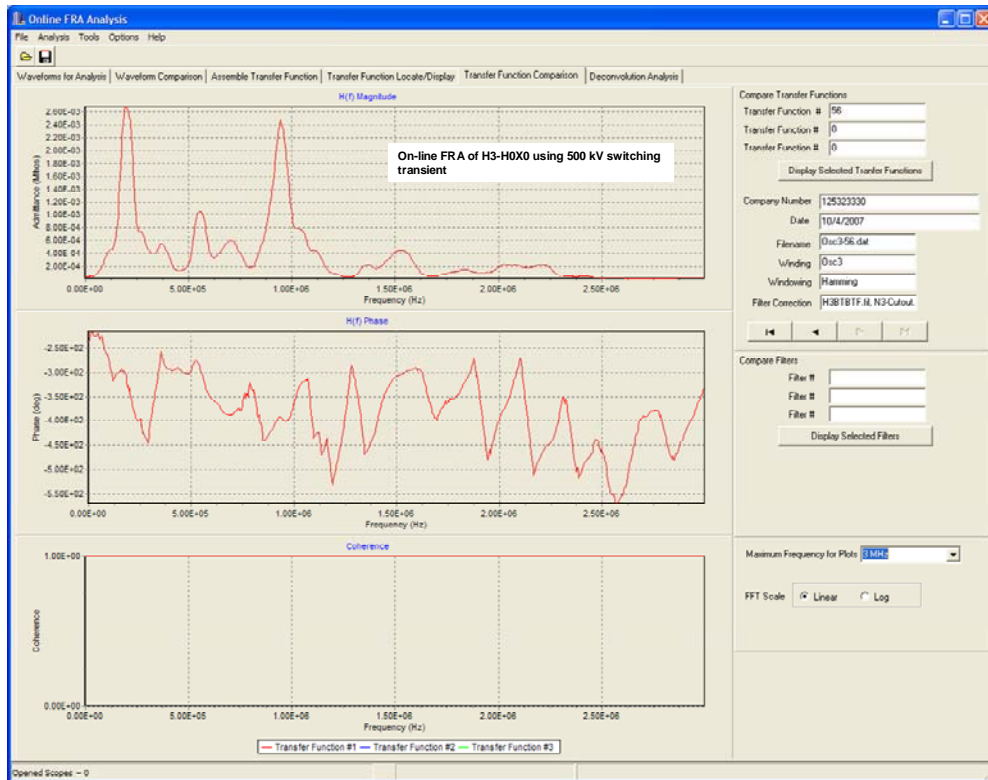
The H3 record of **Figure 13** appears to be one of the higher voltage re-strikes on the switch opening. This open air re-strike offers a fast transition and an estimated 30 kV peak at the top of the H3 bushing which gives an excellent broad band pulse to perform on-line FRA for the H3 winding.



H3, X3, Neutral, and FFT of H3 Bushing Tap Waveform
Figure 13

On-line FRA Measurement

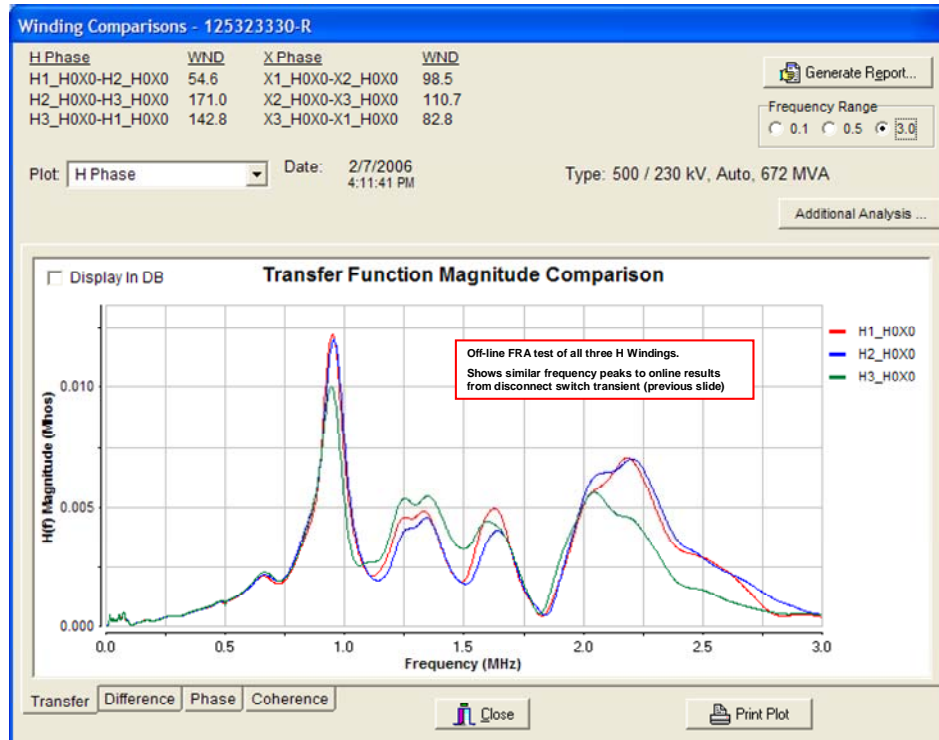
The on-line FRA for the H3 winding is shown in **Figure 14**. As expected from the time domain waveform analysis, the highest resonant peak for the transfer admittance magnitude trace is around 175 kHz for the frequency response analysis as shown in the top trace of **Figure 14**. There are also additional peaks in the 500 kHz to 2.0 MHz region which also correlate with FFT voltages above the baseline for the divider and bushing tap waveforms of **Figures 11 & 12**. This also indicates the sensitivity and accuracy of the FRA technique as compared to analyzing raw time domain waveforms. The low end cutoff for the on-line FRA analysis is about 60 kHz to prevent large 60 Hz and harmonics of same from using up the dynamic range of measurement for the higher frequencies.



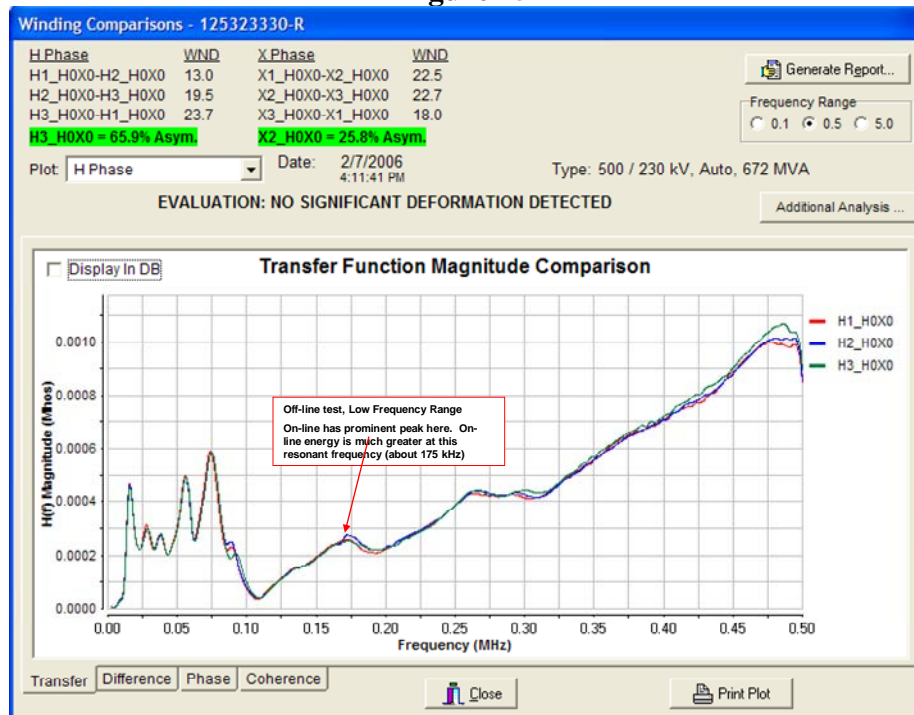
On-line FRA of H3 Winding Using 500 kV Switching Transient
Figure 14

Off-line FRA Measurement Comparison

The frequency of the resonant peaks and the characteristic magnitude shapes for on-line versus off-line can be compared for the frequency range of about 700 kHz to 2.5 MHz. See **Figure 15** to compare off-line FRA. The 175 kHz peak shows up as a much lower level on the off-line test, **Figure 16**, because the energy input off-line, at this frequency, is much smaller than for on-line. The 175 kHz is a natural frequency of the system with lots of energy for the local 500 kV bus and transformer windings combined, and therefore produces a high peak for the on-line FRA.



Off-line FRA of H3, H2, & H1 Displaying 3.0 MHz Range
Figure 15



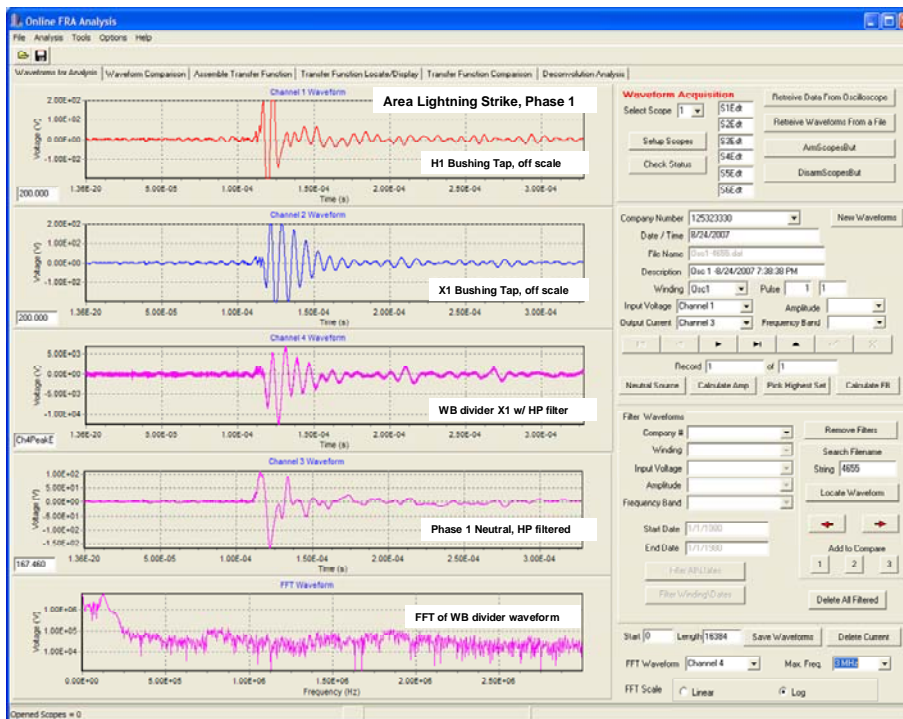
Zoom-in Off-line FRA of H3, H2, & H1 Displaying 500 kHz Range
Figure 16

Lightning Waveforms

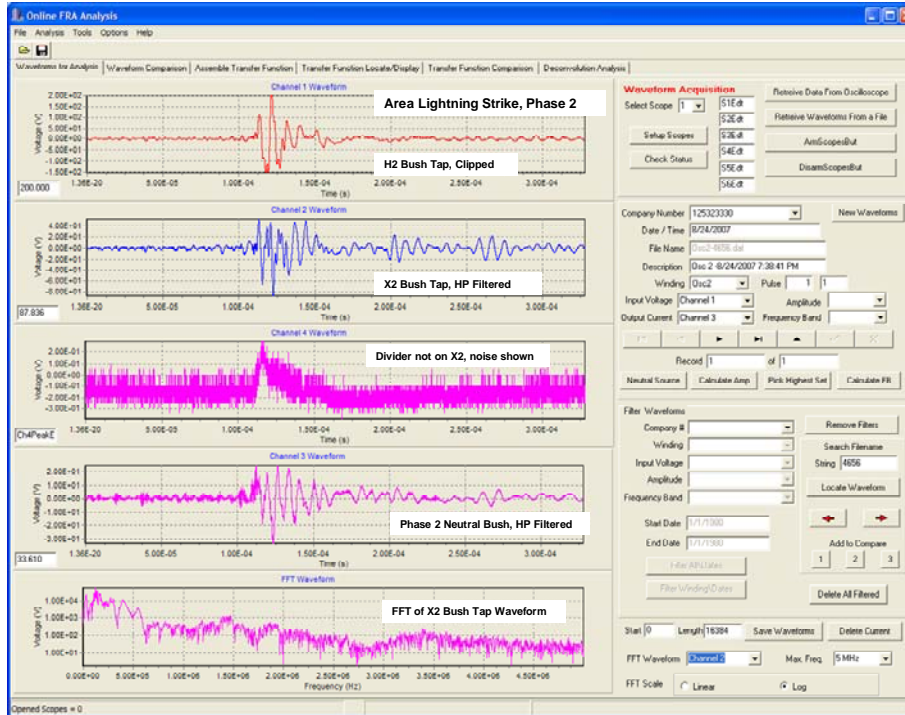
The local area lightning is a good source of on-line pulses to perform on-line FRA. For the most part, these pulses originate some distance from the substation due to induced or indirect lightning strikes to a transmission line. Most of these pulses are in the one to a few tens of kV peak magnitude on arrival to the test transformer.

Figure 17 shows the waveform captures for an area lightning event which happened while the author was sitting in front of the on-line FRA equipment during a small thunder storm. Unfortunately, both the H1 and X1 bushing tap waveform magnitudes railed the attenuator settings at that point, but the waveform for the wideband divider was preserved to show about an 18 kV peak-to-peak value for the X1 bushing input. The FFT of the divider waveform is shown at the bottom of the **Figure 17** which indicates high frequency voltages present.

In addition, it is known that the source of the lightning pulses are from the 500 kV system because the X2 waveform of **Figure 18** is much smaller in magnitude than the H2 waveform in the same figure, and the H2 and X2 captures were made simultaneously. The FFT of the X2 bushing tap waveform at the bottom of **Figure 18** also shows high frequency voltages present.



On-line Lightning Pulse Captures, Phase 1
Figure 17



On-line Lightning Pulse Captures, Phase 2
Figure 18

Switching Transient Observations to Date

- 500 / 230 kV systems can have transients present with frequency content into the MHz region.
- These transients can be generated by local switching and / or lightning.
- High frequencies can pass through a 500 / 230 kV auto with significant energy content to excite resonant frequencies in the windings sufficient for on-line FRA.

Upgrades to a Viable Commercial Prototype at First Energy

To make the on-line FRA & bushing relative power factor equipment combination more viable for commercial use, we must downsize the hardware and make the equipment more user-friendly and cost-effective. We are planning to meet this goal at EPRI's First Energy Star Substation installation while simultaneously increasing the data dynamic magnitude and frequency range as well as increasing the data accuracy and repeatability. The on-line FRA upgrades for First Energy are summarized in the following steps:

1. Remove the FRA development test trailer and the long input signal cables shown in **Figure 8**. The trailer was convenient for a temperature controlled work environment with a desktop computer and laboratory or first generation laptop oscilloscopes to capture the transient signals as shown in **Figure 9**. For First Energy, the computer will be downsized to an industrial Pentium IV board mounted in the OMIPFLive[®], relative power factor (RPF) enclosure on the side of the test transformer. The on-line FRA software, written by JMX Services, Inc.,

and the RPF software, written by On-line Monitoring, Inc. will reside in this computer. The vulnerable hard drive will be replaced with USB memory sticks. No cooling should be required for this computer with only a small amount of heating required for extreme cold conditions. A computer design similar to this one has performed well in the substation PFLive[®] equipment for many years.

The long signal cables previously used were double shielded, tri-axial cables with proper terminations, but cable lengths of 50ft to 150ft allowed some effects due to multiple cable ground loops. There were also some signal distortions due to injected noise and transmission line effects created from fast rise input pulses. These effects can be virtually eliminated by placing the digitizers on the side of the transformer. The signal cables will be short and the transformer tank makes an excellent low inductance ground plane for a wide band of signal frequencies.

The Winding FRA & Bushing RPF enclosures can be relocated to other transformers in the future without an outage on the existing transformer. The low-cost high pass filters, their enclosures & bushing pigtailed can remain on the existing transformer. See **Figure 19**. For example, the existing transformer will be on-line FRA and on-line RPF ready for a future return of the equipment without requiring a transformer outage. Likewise, any future installations can be pre-prepared for the on-line winding FRA and bushing RPF equipment.

2. Replace 6 two channel “laptop” oscilloscopes with 3 four channel “laptop” oscilloscopes. The existing earlier vintage two channel scopes were not available in a four channel version at a fast enough sampling rate. Therefore, two scopes were required for each phase of the transformer mandating a total of 6 scopes to capture the required signals on a 3 phase transformer. In the last year four channel, 12 bit, commercial laptop scopes became available with a speed of 50MHz per channel and long record lengths. These scopes will also make the external trigger box to synchronize the 2 two channel scopes obsolete. These new scopes to be used at First Energy will occupy only a fraction of the space of the 6 existing scopes plus trigger box.

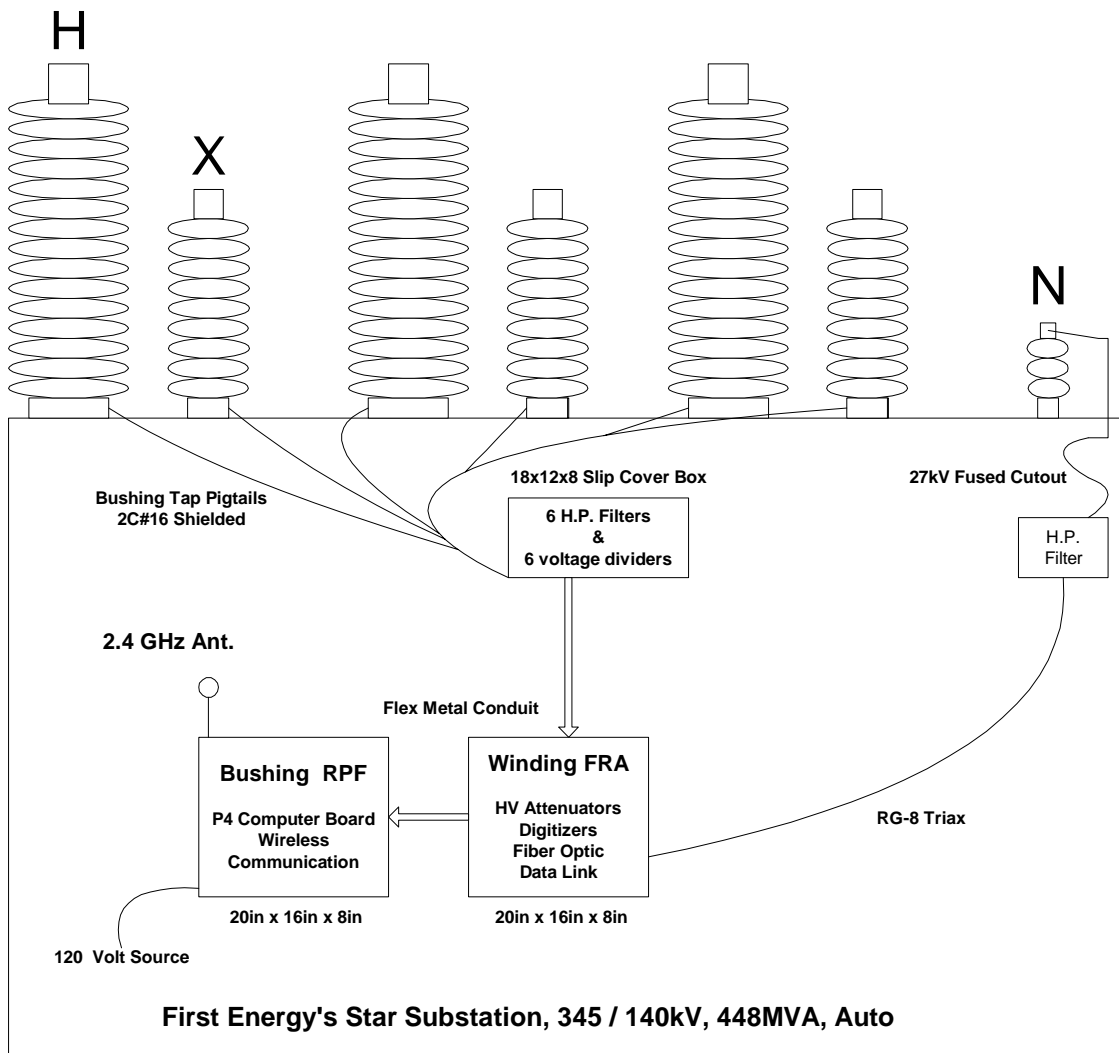
The new scopes should also increase good data by decreasing the data capture-to-capture time from 3 to 4 seconds to about 1 second. For example, the faster data turn-around time will provide at least two data captures per phase on opening a 500kV, and probably a 345kV, disconnect switch.

3. A pdf report format will be added to the on-line FRA program to publish selected on-going FRA results on a website for customer viewing. Access will be password protected. Our goal is to use the results of this project to establish criteria for three alarm states. A GREEN indication for “no significant winding / insulation change,” a YELLOW indication for a “detectable but not significant change,” and RED for “significant winding deformation and/or insulation degradation.” The software comparison of two sets of winding FRA data are defined by an event date. The event date can be manually or remotely chosen by

the user to be the time for a known through-fault or other system event. A default may be chosen to produce a previous year winding FRA signature comparison to the current year. Even a yearly check of winding deformation and / or insulation degradation is more frequent than relying on removing the transformer from service for an off-line FRA test.

The existing 16k data records will be upgraded to 64k data records. This will increase overall data accuracy and produce smaller frequency bins in the frequency domain that will enhance the magnitude and phase plot definition, especially for the lower frequencies.

4. Remote communication to the First Energy computer network is made available with 2.4MHz substation proven, line-of-site, ethernet wireless from the FRA and RPF test equipment on the transformer to the Star Substation network computer. Therefore, no substation yard cabling is required to install the new equipment.



Equipment Location & Interconnection Diagram
Figure 19

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